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COST ANALYSIS OF THE PERFORMANCE OF CO_2 SEPARATION WITH VARIOUS CO_2 CONCENTRATIONS FROM GAS WELLS

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ABSTRACT

The technical and economic challenges are enormous in developing gas wells with a high CO_2 *content (> 50 mol %), such as the East Natuna gas field, which has 71 mol % (86 mass %). Carbon capture technology in gas wells with high* CO_2 *content is studied to find a more economical one. In this study, the technology for capturing high concentrations of* CO_2 *is varied from gas wells, Controlled Freeze Zone (CFZ), and cryogenic distillation which will be analyzed based on cost. Variations in the* CO_2 *content of gas wells are 75 %, 80 %, 85 %, 90 %, and 95 % in mass fraction simulated using Aspen Plus V.11.0. Based on this research, CFZ technology and cryogenic distillation can obtain purity up to 99 % and recovery above 78 %. However, the total annual cost (annual capital and operating costs) of CFZ technology is lower than cryogenic distillation technology, so CFZ technology is suitable for capturing* CO_2 *in gas wells with high* CO_2 *content.*

Keywords: carbon capture, CFZ, cryogenic distillation, process simulation, cost analysis.

INTRODUCTION

In the development of global energy, Carbon Capture Utilization and Storage (CCUS) is increasingly becoming an important issue to be discussed to reduce CO_2 concentrations in the atmosphere below 350 ppm [1]. One of the main challenges for implementing a Carbon Capture Storage (CCS) system on a large scale is the high cost of the CO_2 capture process [2]. Mualim et al. designed a carbon management system for Carbon Capture, Storage and Utilization (CCSU) in Indonesia to reduce emissions from industry [3]. Meanwhile, the concept of carbon capture, utilization, and storage (CCUS) is a top priority, especially in CO_2 -Enhanced Oil Recovery (EOR) or Enhanced Material Recover (EMR) to increase oil recovery [4, 5]. As an alternative to geological storage, high-purity CO_2 is captured and then used to extract crude oil from oil fields connected by pipeline transportation [6, 7]. High energy consumption, purity, and low CO_2 recovery are challenges for CO_2 capture technology, so it is necessary to look for a combination of CO_2 capture technologies [8].

On the other hand, natural gas wells with high carbon dioxide (CO_2) concentrations are scattered worldwide, especially in Southeast Asia. Techno-economic separation hampers commercial development to obtain high concentrations of CO_2 [9]. Regionally, high CO_2 gas fields were identified as areas for further technology development. Future challenges require anticipation in creating an effective and efficient CO_2 capture process. Most of the research report is based on the utilization of CO_2 captured from natural gas, indicating an inevitable increase in the cost of carbon capture. This causes the absence of CO_2 capture from gas wells such as the East Natuna gas field, which has natural gas reserves of 222 Tcf with a CO_2 content of 71 mol % (86 mass %) [10].

Researchers are still developing technologies that can be applied in industries that are more economical and practical. The concentration of CO_2 that can be removed by current methods, such as liquid absorption employing amines and physical solvents, Controlled Freezing Zones (CFZ^{TM}), and membrane penetration, is limited at 60 % v/v. [10]. Absorption, adsorption, membrane separation, and cryogenic distillation are commonly used technologies for sweetening natural gas. Based on a review by Hinkov et al., the gas-solid adsorption technique is unsuitable for high amounts of flue gas except for low CO_2 concentrations with the purity of CO_2 capture below 90 %. The increased ability of the adsorbent can be combined by impregnation with amines which causes the selectivity of the adsorbent to increase 5 - 10 times higher [11]. However, of these processes, the most frequently used process for sweetening natural gas is chemical and physical absorption.

Environmental issues may be getting worse because of the separation of membranes used for CO_2 removal. The purification of natural gas with a CO_2 content of more than 50 mol % and H_2S up to 10 mol % is best accomplished using membrane-based acid gas removal technology [12]. The flexibility of membrane technology for high energy efficiency serves as an indication of its development. Membrane separation is more cost-effective and environmentally sustainable than absorption due to the lack of chemical solvents [13]. In addition to the previously mentioned methods, cryogenic distillation technology is presently the subject of additional research and development. It has been frequently applied in medium- to large-scale plants to produce nitrogen, oxygen, and argon.

Cryogenic technology is preferable as it is most economical for regions with high CO_2 concentrations and plants that produce oxygen and nitrogen purity at high rates. Cryogenic distillation reduces H_2S and CO_2 from the gas phase to a liquid or solid phase, valorizing the product by reducing the temperature to below 73.3^{o}C using a refrigeration system [14]. The primary benefit of this method is that it may generate liquid $CO_{2,}$ which is prepared for transport to storage or utilization locations. This technology has the benefit of not using water or solvents, which can increase the expense of the CO_2 removal procedure [12]. However, many physical or chemical procedures, such as membrane processes, adsorption, and absorption, can also be choices for separating CO_2. Even though some technologies are thought to be capable of capturing CO_2, not all have at least 90 % recovery and purity for all sources with various compositions. [7].

According to the research of Nizami et al., the CFZ-based separation process can capture CO_2 at 97.54 % and hydrocarbon recovery at 95.40 %. The results show better performance compared to the membrane-based with CO_2 capture of 95.78 % and 92.92 % of hydrocarbon recovery. CFZ technology shows better performance compared to membrane–based [10]. Similar results were obtained by Yousef et al., simulating the separation of CO_2 from biogas using cryogenic distillation produced 99.92 % purity [15]. So that the researchers in this study will evaluate the performance of CO_2 capture technology using CFZ and cryogenic techniques by cost analysis. The feed gas in this study is based on gas wells with high CO_2 concentrations, such as the East Natuna field. Variations in the CO_2 content used for evaluating CFZ and cryogenic technology are 75 %, 80 %, 85 %, 90 %, and 95 % in the mass fraction, emphasizing changing the composition of CO_2 and CH_4 in the feed stream.

EXPERIMENTAL

The primary component of this work included process modeling using Aspen Plus V.11.0 and Peng-Robinson (PR) as the thermodynamic property package, with the assumption that the system is a binary mixture of CO_2 and CH_4 and that CO_2 is the only solid component. In order to calculate the fugacity coefficients (ϕ) of each gas component for both the solid vapor equilibrium (SVE) and the solid-liquid equilibrium (SLE), the PR-EOS is primarily used [16]. The simulation was validated using data from the research of Nizami et al. which the feed used was from the East Natuna Gas well shown in Table 1.

In his study, the gas well flow rate is 4253.29 ton h^{-1} at a temperature of -52^{o}C and a pressure of 38 bar after treatment as feed for CFZ and Cryogenic Distillation. The CH_4 content in the feed stream follows the variable variations in the CO_2 content, while the other compositions of components remain constant. This aims to determine how capturing CO_2 from the stream that exists from the gas well will change as CO_2 and CH_4 compositions change. Data on variations in CO_2 content in gas well feed streams with high CO_2 concentrations used in simulations to evaluate CFZ and cryogenic performance are shown in Table 2.

Table 1. Operating condition at Natuna Gas Well [10].

Feed comp.	% mol	Molar flowrate (MMSCFD)	% mass	Mass flowrate, ton h^{-1}
C_1	26.99	635.07	11.93	507.42
C_2	0.51	12.03	0.42	17.97
C_3	0.16	3.76	0.19	8.27
I-C_4	0.04	0.94	0.06	2.73
N-C_4	0.04	0.94	0.06	2.73
I-C_5	0	0	0	0
N-C_5	0	0	0	0
N-C_6	0.01	0.23	0.02	1.01
N-C_7	0.01	0.23	0.03	1.17
N-C_8	0	0	0	0
N_2	0.41	9.65	0.32	13.46
H_2S	0.52	12.24	0.49	20.77
CO_2	71.31	1677.92	86.47	3677.77
H_2O	0	0	0	0
O_2	0	0	0	0
Total	100	2353	100	4253.29
Pressure, bar	62			
Temperature, °C	40			

Table 2. Variation of CO_2 content in the feed stream after treatment.

Feed Comp.	Natuna Gas Well	Variation of CO_2 in Feed				
	% mass	% mass	% mass	% mass	% mass	% mass
C_1	11.93	23.40	18.4	13.4	8.40	3.40
C_2	0.42	0.42	0.42	0.42	0.42	0.42
C_3	0.19	0.19	0.19	0.19	0.11	0.19
I-C_4	0.06	0.06	0.06	0.06	0.03	0.06
N-C_4	0.06	0.06	0.06	0.06	0.03	0.06
I-C_5	0	0	0	0	0	0
N-C_5	0	0	0	0	0	0
N-C_6	0.02	0.02	0.02	0.02	0.01	0.02
N-C_7	0.03	0.03	0.03	0.03	0.01	0.03
N-C_8	0	0	0	0	0	0
N_2	0.32	0.32	0.32	0.32	0.29	0.32
H_2S	0.49	0.49	0.49	0.49	0.36	0.49
CO_2	86.47	75	80	85	90	95
H_2O	0	0	0	0	0	0
O_2	0	0	0	0	0	0
Total	100	100	100	100	100	100
Total	4253.29	4253.29	4253.29	4253.29	4253.29	4253.29

Configuration for cryogenic distillation and CFZ using two radfrac columns on Aspen Plus V.11.0 In this study, the CFZ simulation and cryogenic distillation technology on Aspen Plus V.11.0 were simplified where the incoming feed was processed by cooling at -52°C at 38 bar. This simplification simulation was carried out following several studies, such as Daton et al. and Pelegrini et al. when simulating cryogenic distillation technology to capture CO_2 from gas wells [17, 18]. However, in CFZ, a flash separator column is placed before the second radfrac column. Fig. 1 and Fig. 2 show the diagrams for the two CO_2 capture technologies used in this study.

The gas well with varying CO_2 content is fed to the cryogenic distillation column shown in Fig. 1. The feed consists of a mixture of vapor and liquid with different fractions depending on the CO_2 content in the feed. In both columns, it is assumed that there is no change in pressure, so the inlet and outlet pressures remain at 38 bar. The reflux ratio in both columns is set to 2 with a number of stage 20. The feed will enter first column in the second stage then the distillate flow will enter the second column in the 15th stage. The liquid CO_2 compound will exit through the bottom product in the first and second columns.

Unlike the conventional cryogenic method, the Controlled Freeze Zone™ concept involves the controlled freezing and remelting of CO_2 in a specially designed section of a distillation tower. A CFZ™ tower is essentially divided into three zones to separate CH_4 to high purity from acid gas: the specially designed CFZ™ section, which represents the solidification region in the phase equilibrium, and two conventional, rectifying and

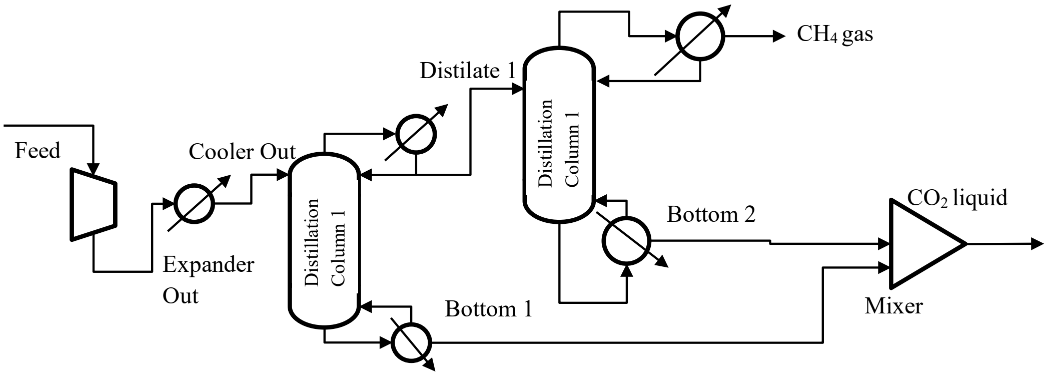

Fig. 1. Configuration of Cryogenic Distillation.

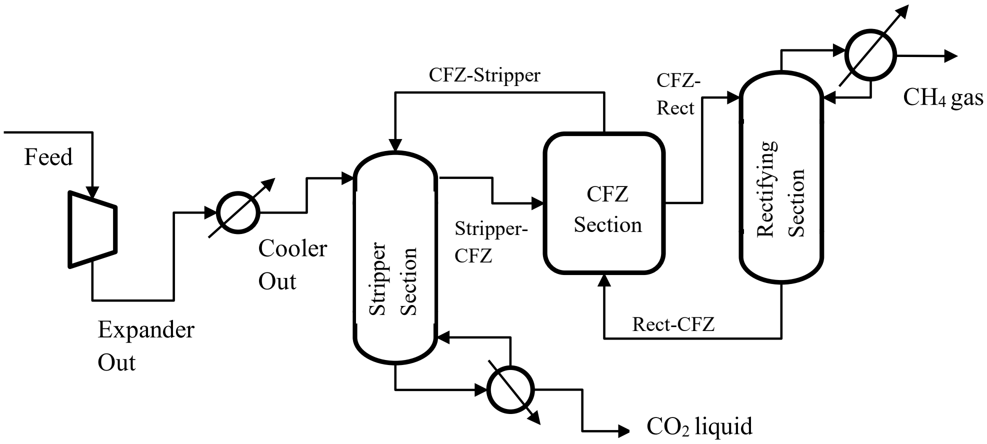

Fig. 2. Configuration of Control Freeze Zone.

stripping sections, which present the vapour-liquid areas above and below the CO_2 solidification region. [19]. The CFZ^{TM} Commercial Demonstration Plant was carried out in a trial phase with the results of 99.5 - 100 % CO_2 as the bottom product and 0.6 % CO_2 in the top product of the CFZ distillation column using feed gas with a composition of 71 % [20]. The CFZ technology shown in Fig. 2 has a flash column as remelting CO_2 section to separate the vapour and liquid phases from the first column. So the compound in the gas phase will enter the second column, and the liquid phase will be returned to the first column. In addition, the flash column in the CFZ also functions to separate the mixture of compounds contained in the bottom product from the second column. The vapour fraction in the flash column is set to 0.9 to maximize the CH_4 that separated and exited in the distillate product of the second column. It is expected that the CO_2 contained in the bottom product of the second column can be separated and exited in the bottom product of the first column.

In addition to purity and recovery, looking at operating and capital costs taken from Aspen Process Economic Analyzer (APEA) is necessary. Based on the lowest Total Annual Cost, the two separation technologies considered in this research will be evaluated (TAC). The method from Luyben (2011) was used to calculate the TAC, represented in Eq. 1 below, and represents the sum of the total energy cost and the total capital cost divided by the payback period [21].

$$TAC = TOC + \frac{TCC}{PB} \tag{1}$$

where:

TAC : Total Annual Cost (USD/years)
TOC : Total Operating Cost (USD/year)
TCC : Total Capital Cost (USD)
PB : Payback period (years)

RESULTS AND DISCUSSION

The process simulation carried out in this study was validated using data from the research of Nizami et al. [10]. In a previous study, CFZ technology simulated using Aspen Hysys separated CO_2 from the East Natuna gas well flow by 97.54 %. Based on the validation results using Aspen Plus V.11.0 obtained CO_2 of 98.86 % with a validation error of about 1.32 %. Next, evaluate the performance of CO_2 capture technology using CFZ and cryogenic techniques with variations in the CO_2 content of 75 %, 80 %, 85 %, 90 %, and 95 % in mass fraction. The configuration of cryogenic technology and CFZ, which is simulated using Aspen Plus V.11.0 can be seen in Fig. 1 and Fig. 2.

The simulation results of cryogenic distillation and CFZ technology in capturing CO_2 at various CO_2 content are shown in Fig. 3. The separation of CO_2 using the two technologies did not show a significant difference in the recovery and purity resulting from the simulation. Both technologies can capture CO_2 with

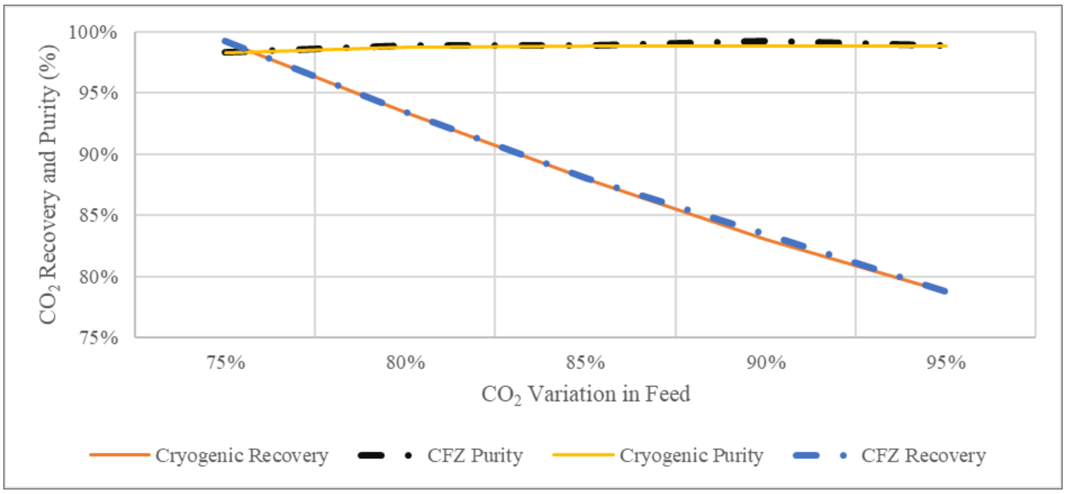

Fig. 3. CO_2 recovery and purity in cryogenic distillation and CFZ with variations CO_2 content in feed.

recoveries above 78 % and more than 98 % purity. This is because the two technologies share the same principle and can capture CO_2 at very low temperatures.

As stated by Zhang et al., CO_2 captured for commercial products such as extracting crude oil from oil fields or CO_2-EOR requires high purity (95 %) so that CO_2 obtained from the simulation results of these two technologies can be used for utilization such as EOR [7]. Sufficient carbon dioxide is required to increase oil recovery, especially in low-permeability reservoirs [22 - 25]. There are three common techniques for producing oil using carbon dioxide injection: immiscible flooding (injection pressure less than minimum miscible pressure; mixed flooding (injection pressure greater than MMP), and supercritical carbon dioxide flooding (injection pressure and temperature above critical temperature and critical pressure). These three techniques use a lot of CO_2 [22, 25 - 28].

Obtaining high purity and recovery will increase operating costs and energy consumption, so it is necessary to calculate Total Annual Cost (TAC). The TAC was calculated based on Eq. 1, which is the sum of total energy costs and total capital costs divided by the payback period. The payback time for this research was set at 3 years. The cost Comparison between CFZ and Cryogenic Technology shows in Table 3.

Data on total energy cost or operating cost (TOC) and total capital cost (TCC) were obtained from the calculation results of the Aspen Process Economic Analyzer (APEA). Based on Table 3, TCC and TOC in CFZ technology are lower than cryogenic in all variations of CO_2 content. CFZ technology has the lowest TAC value, 14 050 390 USD/year, at 95 % variation of CO_2. Cryogenic technology has the highest TAC of 58 255 103 USD/year. This can be due to the energy requirements of CFZ, which are not too high compared to cryogenic technology. The existence of a flash column as a controlled freeze zone in the CFZ can reduce the energy required to capture CO_2.

Fig. 4 and Fig. 5 show a comparison of the total annual cost in obtaining recovery and purity of various variations of CO_2 in the feed. The method of economic aspect calculation is the Total Annual Cost (TAC) method, a combination of Total Operating Cost and Annualized Capital Cost. Annualized Capital Cost is the annualized value total of capital cost invested in the operation unit used, such as compressor, heater, and cooler, and operating cost invested in steam, electricity, and refrigerant. The Total Operating Cost is the cost incurred by the process operation, such as raw materials and energy costs [29]. The cryogenic distillation technology, shown in Fig. 4, gets 99.19 % recovery and 98.31 % purity and TAC of 61 718 997 USD $year^{-1}$ at 75 % CO_2 variation. Whereas in Fig. 5, the CFZ

Table 3. Cost comparison between CFZ and Cryogenic technology.

CO_2 content in feed (%)	Capture Technology	TCC (USD)	TCC/PB (USD/year)	TOC (USD/year)	TAC (USD/year)
75	CFZ	47 185 300	15 728 433	7 337 890	23 066 323
	Cryogenic	94 878 200	31 626 066	30 092 930	61 718 997
80	CFZ	102 949 000	34 316 333	7 927 540	42 243 873
	Cryogenic	115 052 000	38 350 666	35 196 233	73 546 901
85	CFZ	50 656 500	16 885 500	7 691 620	24 577 120
	Cryogenic	94 416 300	31 472 100	36 228 165	67 700 266
90	CFZ	32 688 200	10 896 066	9 233 400	20 129 467
	Cryogenic	57 514 400	19 171 466	36 721 317	55 892 784
95	CFZ	18 585 900	6 195 300	7 855 090	14 050 390
	Cryogenic	48 738 500	16 246 166	42 008 936	58 255 103

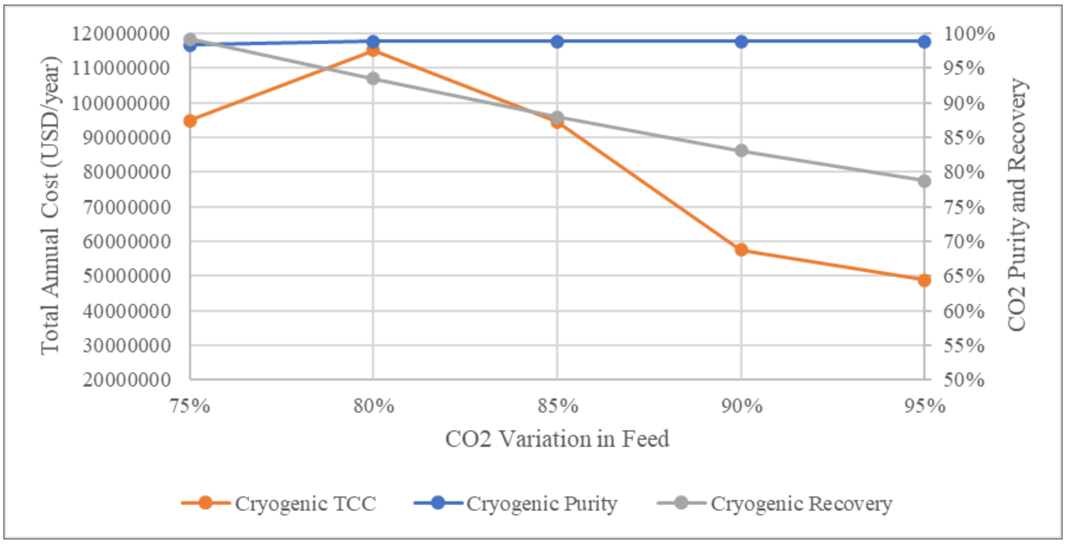

Fig. 4. Total annual cost in Cryogenic technology.

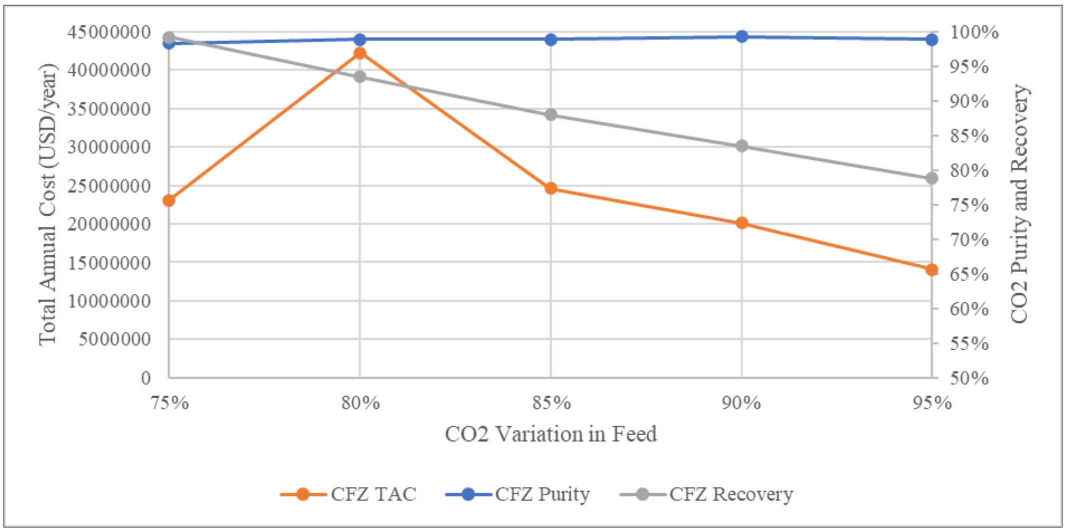

Fig. 5. Total annual cost in CFZ technology.

technology can produce 99.28 % purity and 83.47 % recovery with the TAC of 20 129 467 USD year^{-1} at 90 % CO_2 variation.

However, compared to the total annual costs obtained by both technologies, CFZ technology is lower than cryogenic distillation technology. It can be due to the requirement for refrigerant in the two different technologies. In cryogenic distillation, ethane is a refrigerant, while in CFZ technology, ethane and propylene are used as refrigerants. The total refrigerant cost is based on the sum of every condenser's heat duty. Even though the small price of the refrigerant, the calculated mass load demands a huge amount of refrigerant. Therefore, it is required to include refrigerant in the operation cost [30]. In addition, CFZ only requires one reboiler in the first column and one condenser in the second column, while cryogenic distillation requires a condenser and reboiler in both columns. So, the operating cost of cryogenic distillation is higher than CFZ.

The cost of capturing CO_2 using CFZ technology is still in Font-Palma et al. range, around 55-130 USD/ton CO_2 (55 - 130 million USD/Mt CO_2) [31]. Although the cost of capturing CO_2 using CFZ technology is higher than other CO_2 capture technologies, CFZ technology can produce the highest recovery of 99.22 %. Meanwhile, the absorption technology studied by Putra et al. resulted in a recovery of 85.37 % [32]. Ariani et al. studied the effect of absorbent promoters in removing CO_2 using packed columns with a raschig ring. Based on the analysis results, the best operating conditions for CO_2 absorption are using DEA, which can capture CO_2 of 42.7 % [33].

In addition to the recovery obtained, the purity of CO_2 obtained using CFZ technology is relatively high, 99.28 %, while the cryogenic technology has a lower purity, 98.82 %. According to the research by Song et al., cryogenic technology will produce higher purity when combined with other technologies [34]. Research by Grande and Blom succeeded in capturing 99.99 % CO_2 from natural gas using a combination of cryogenic and adsorption technology [35]. In other words, CFZ technology can capture higher CO_2 at a lower cost than cryogenic technology at high CO_2 concentrations in the feed.

CONCLUSIONS

Based on this study, the separation of CO_2 using CFZ and cryogenic distillation did not show a significant difference in the recovery and purity resulting from the simulation. Both technologies can capture CO_2 with recoveries above 78 % and more than 98 % purity. In other words, CFZ technology can be used for EOR or other utilization with a total annual cost of 20 129 467 USD/year. So CFZ technology is more applicable in Indonesia, which has gas wells with high CO_2 content, because the total annual cost of CFZ technology is lower than cryogenic distillation technology.

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